Single-frequency diode-pumped semiconductor laser tuned on a Cs transition

Benjamin Cocquelin, Gaëlle Lucas-Leclin, Patrick Georges, Isabelle Sagnes, Arnaud Garnache, David Holleville

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B. Cocquelin, Gaëlle Lucas-Leclin and P. Georges

Laboratoire Charles Fabry de l'Institut d'Optique,
Palaiseau, France

I. Sagnes

Laboratoire de Photonique et de Nanostructures,
Marcoussis, France

A. Garnache

Institut d'Électronique du Sud,
Montpellier, France

D. Holleville

LNE/SYRTE - Observatoire de Paris ,
Paris, France

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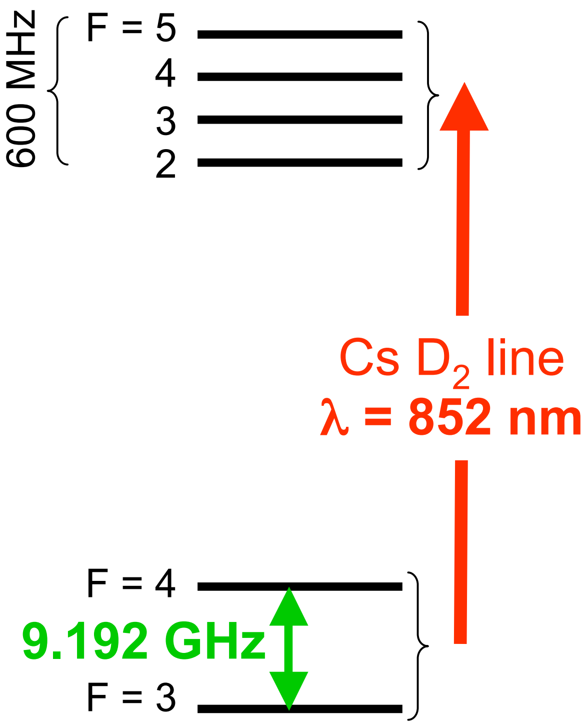
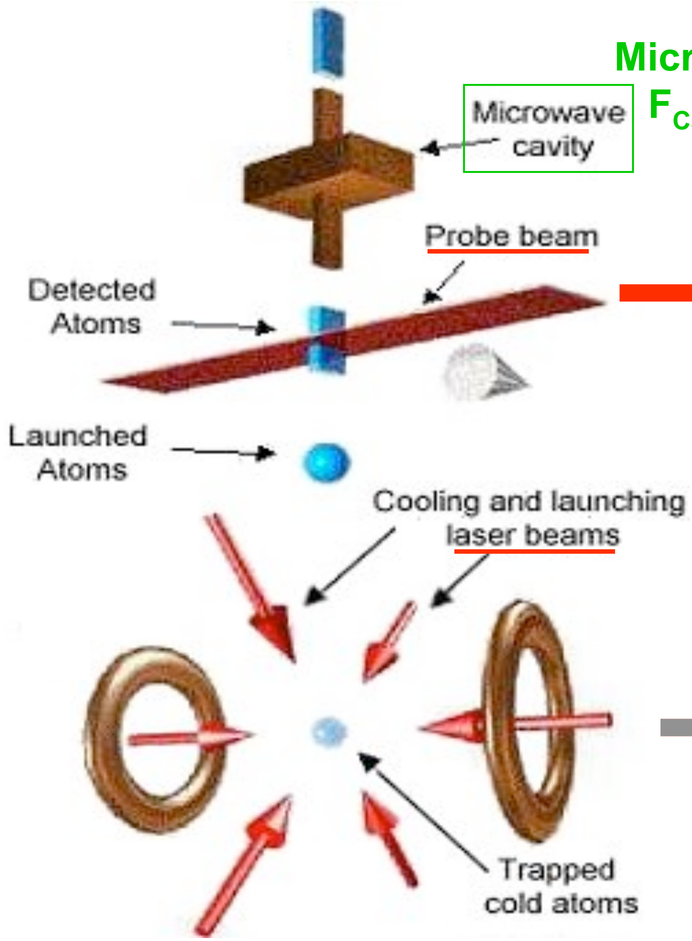
Lasers in Cesium atomic clocks



Cs atomic levels



Scheme of an atomic fountain

Microwave interrogation :
F_{Cs} = 9 192 631 770 Hz

Optical Detection

$\Delta\nu \ll 5$ MHz

Extended-cavity laser diodes

Atom cooling

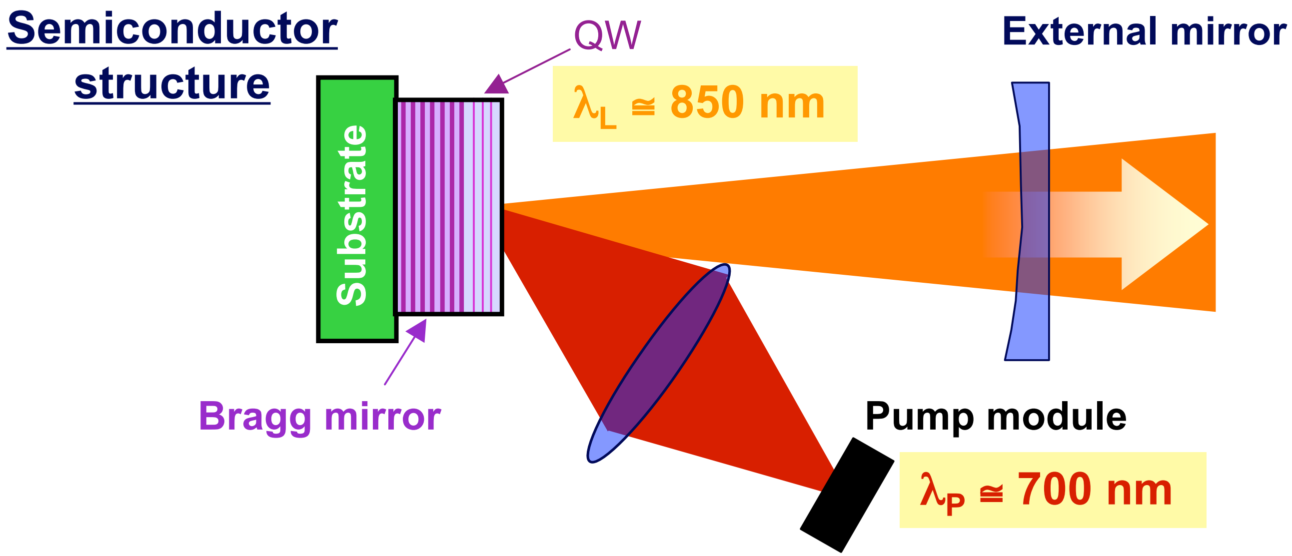
$P_{opt} > 200$ mW

DFB/DBR diodes, MOPA, …

Need for **high-power** and **narrow-linewidth** sources emitting at the Cesium D_2 line (852 nm)

$\Rightarrow$ *a single OP-VECSEL ?*

OP-VECSEL at 850 nm



- **High power** in Optically Pumped-VECSEL

  30 W @ 980 nm, $M^2 = 3$ (Coherent - Photonics West '04)

  1.0 W in-well pump / 0.7 W @ 850 nm, $M^2 = 5$ (University of Strathclyde)

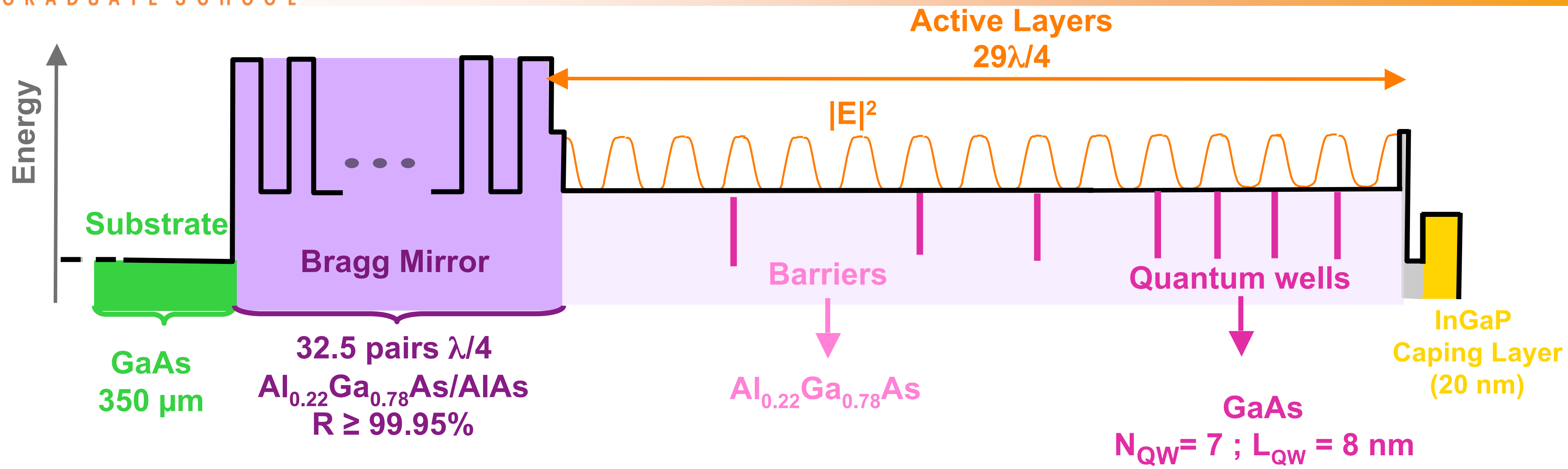
- No spatial hole-burning : **single-frequency** in simple linear cavity

  500 mW @ 1003 nm (Jacquemet et al, App.Phys. B 86, 503 (2007))

  42 mW @ 870 nm, $\Delta\nu_L \cong 3$ kHz (Holm et al, IEEE PTL 11, 1551 (1999))

- Linearly polarized, circular TEM_{00} beam

Design of the semiconductor structure



- λ_L = 852 nm
- Barriers absorption at $\lambda_P \leq$ 720 nm

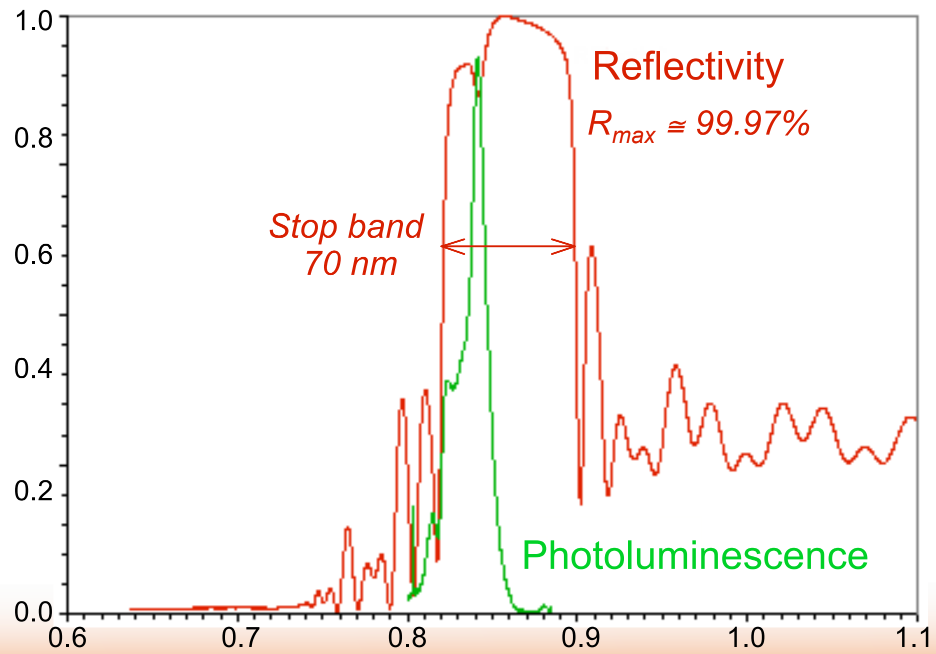
  $e_b \cong 2$ µm $\Rightarrow \eta_P = 85\%$

- AR coating (Si_3N_4) at air/SC surface for :

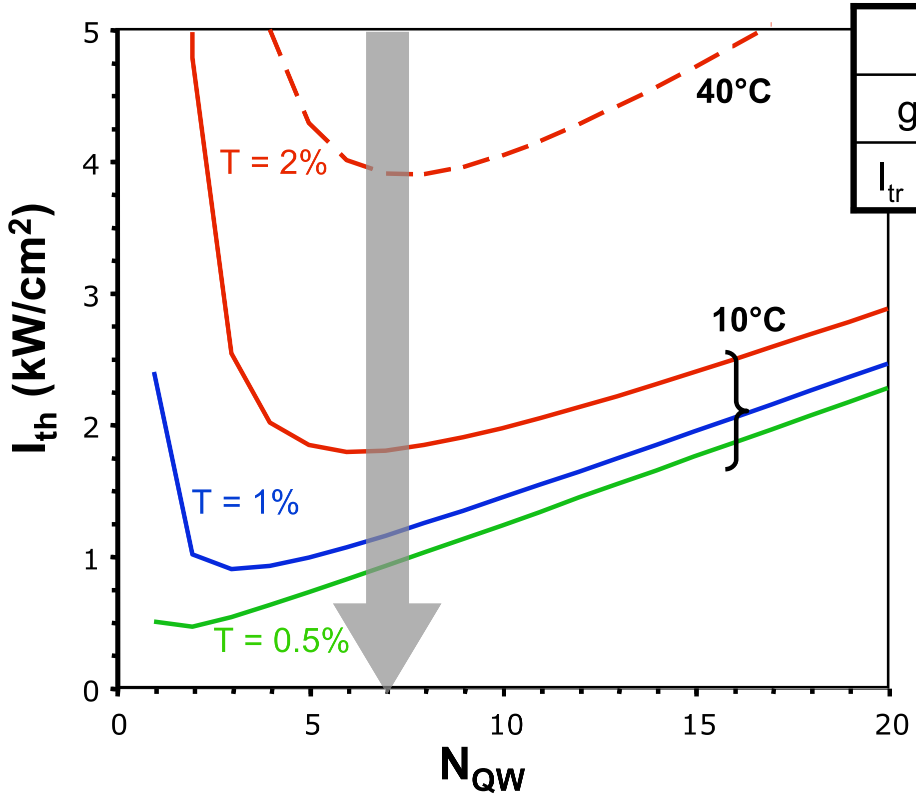
  maximum pump transmission

  + reduction of microcavity etalon effect

- Structure grown by MOCVD



Design optimization



T(°C)	10°C	40°C
$g_0(cm^{-1})$	1000	830
I_{tr} (W/cm²)	105	190

Experimental parameters

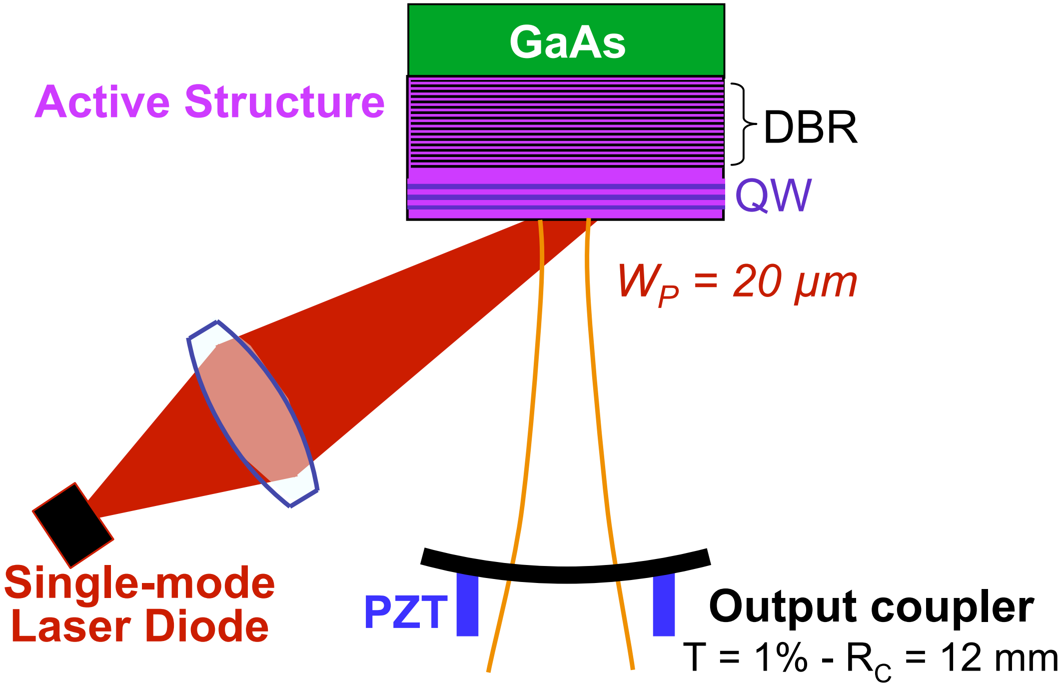
Threshold intensity

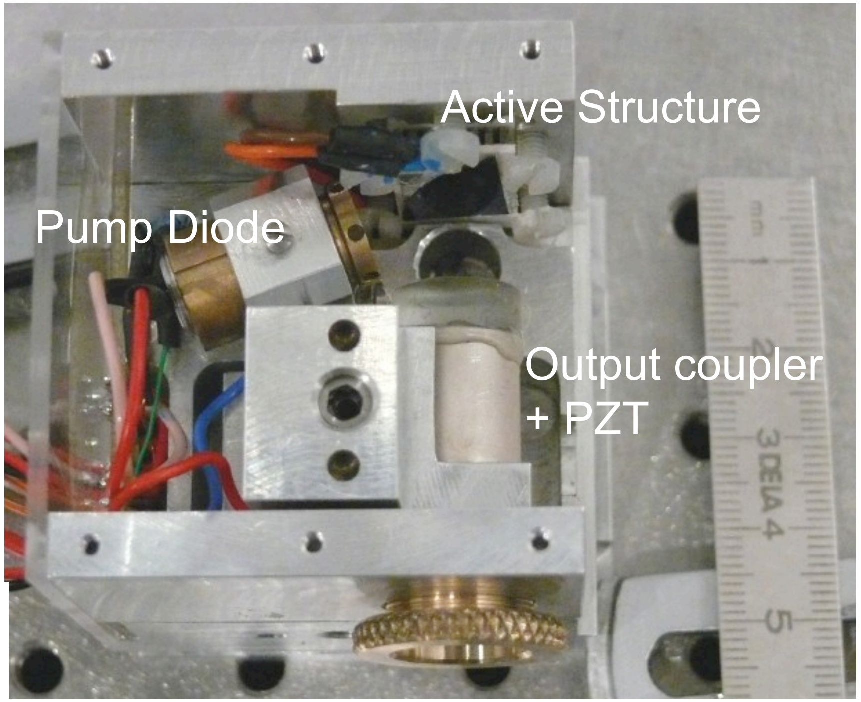
$$I_{th} = N_{QW} I_{tr} \times \exp\left(\frac{T}{2\Gamma N_{QW} L_{QW} g_0}\right)$$

- Low threshold pump intensity I_{th} for high opt-opt efficiency

$\Rightarrow$ N_{QW}= 7 is optimal for ~ 2% losses

Single-frequency setup

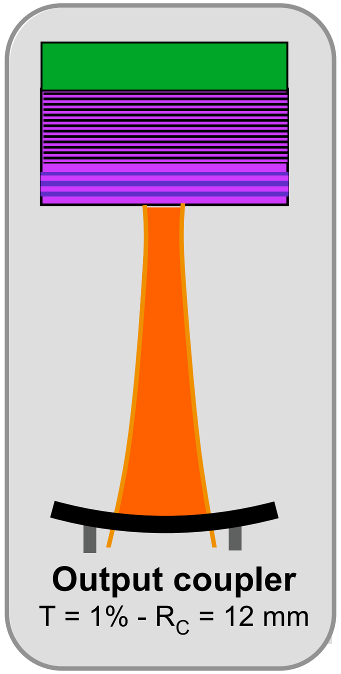


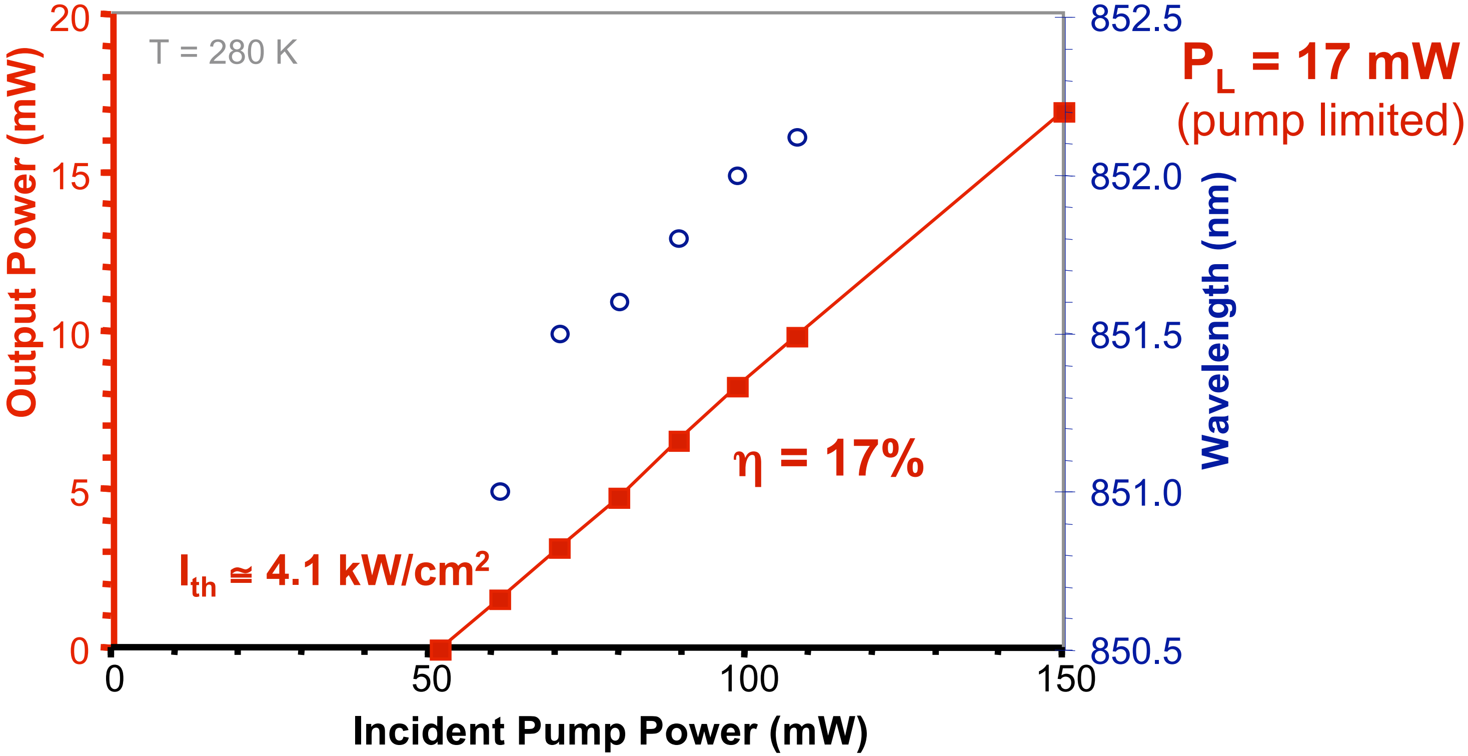


- Compact plane-concave cavity : $L_{ext} \cong 10$ mm
- Single-transverse mode pump laser diode :

  P_{max}= 120 mW (245 mA) at λ_P = 658 nm
- 52 x 52 x 58 mm^3 integrated setup for improved mechanical stability

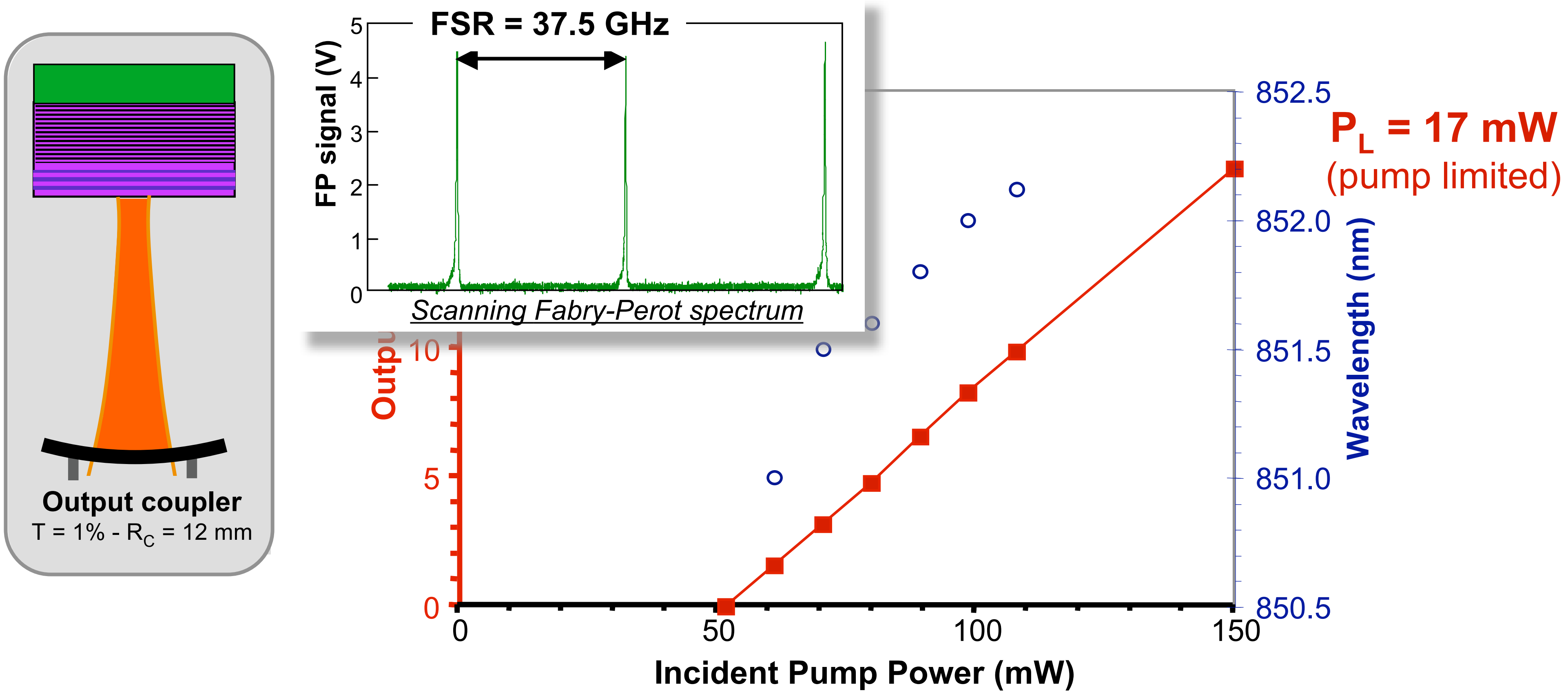
Single-frequency emission





- Low threshold: 4.1 kW/cm²
- Good beam quality : M² < 1.2 and linear polarization

Single-frequency emission



- Single frequency operation **without intracavity λ-selective element** :

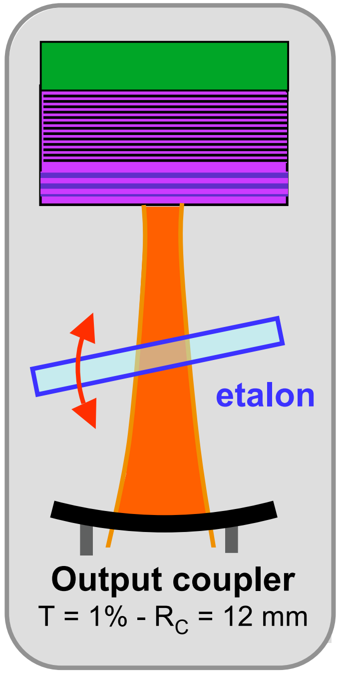
  checked with a high Finesse (F = 130) 37.5-GHz-FSR scanning Fabry-Perot

  SMSR > 25 dB

Single-mode spectrum in $t_{SM} \cong T_C \left(\frac{\Gamma}{FSR} \right)^2 \cong 1\text{ms}$ for L_{ext} = 10 mm $\begin{cases} T_C = \text{photon lifetime (~ 10 ns)} \\ \Gamma = \text{gain bandwidth (~ 10 nm)} \end{cases}$

Jacquemet et al, App.Phys. B (2006)

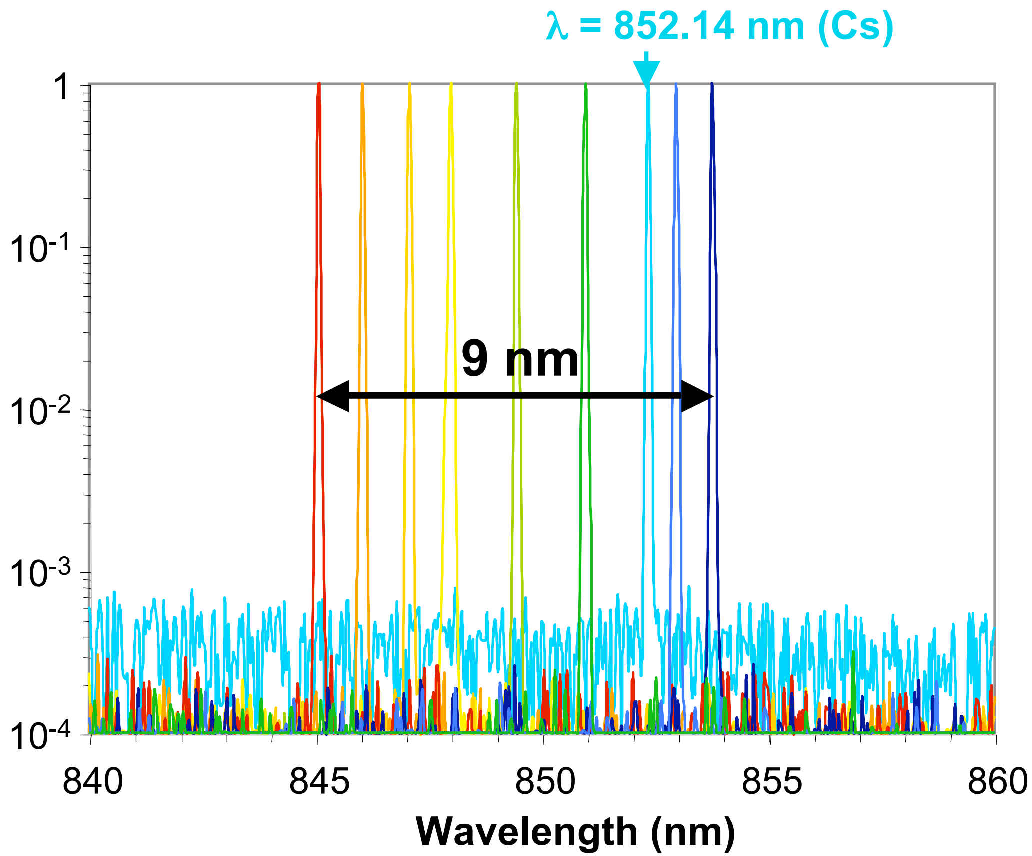
With an intracavity etalon



25-µm thick (≅ 9 nm FSR) silica etalon

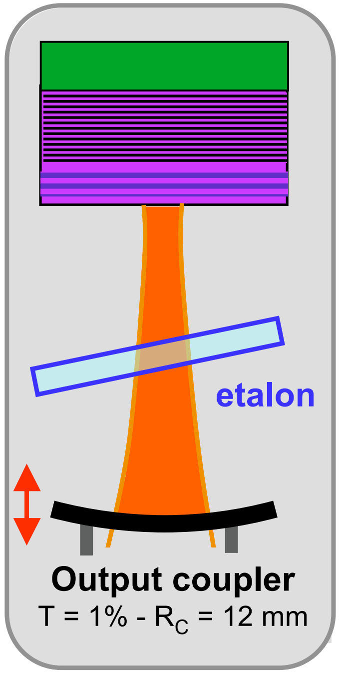
$\Rightarrow$ λ independent of operating conditions (T°, P_P)

+ improved long-term stability

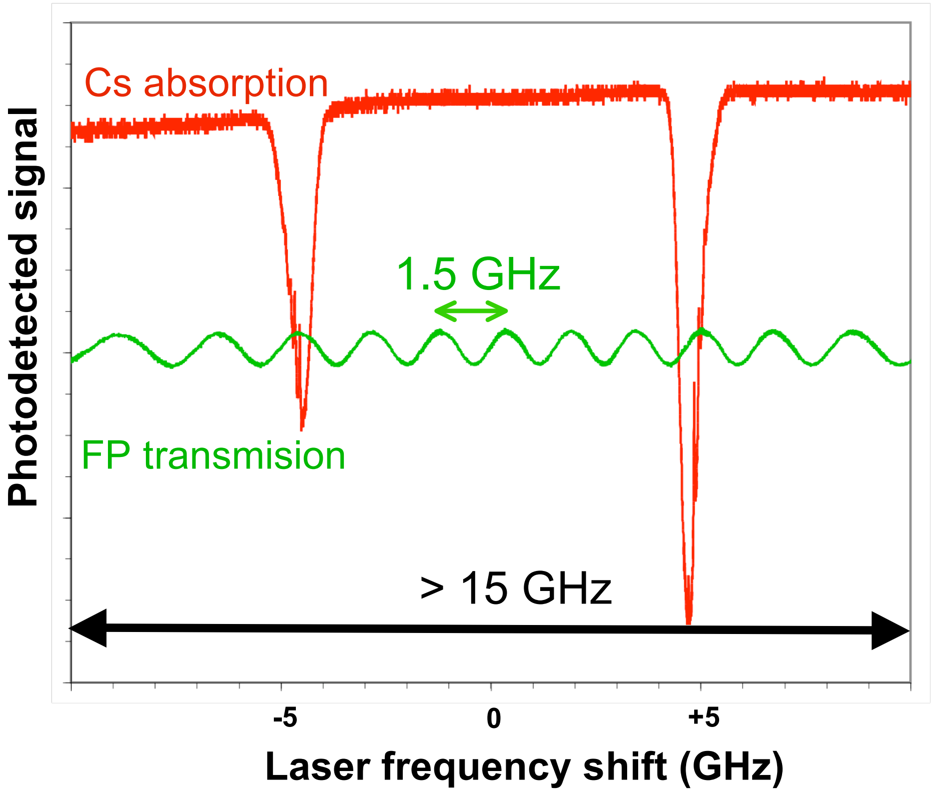


• Increased losses at $\theta \neq 0°$ $\Rightarrow$ ↘ laser power : P_L = 7 mW @ 852.14 nm

Single-frequency tunability



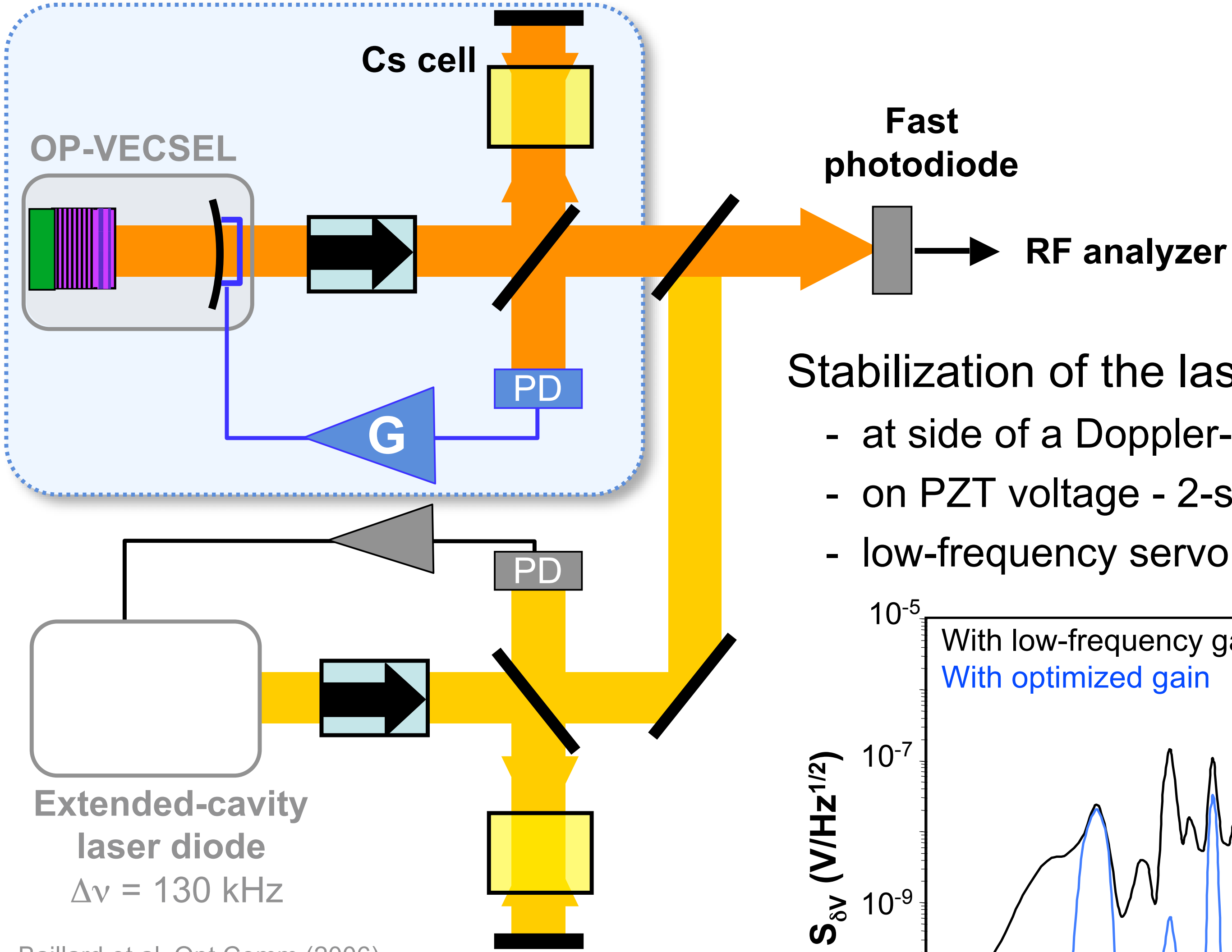
- more than 15 GHz continuous tunability (without mode-hops) by translating the external cavity mirror with PZT



Frequency-shift measurement with a low-finesse static 1.5-GHz-FSR Fabry-Perot

$\Rightarrow$ Tuning over the Cs-absorption spectrum (9 GHz)

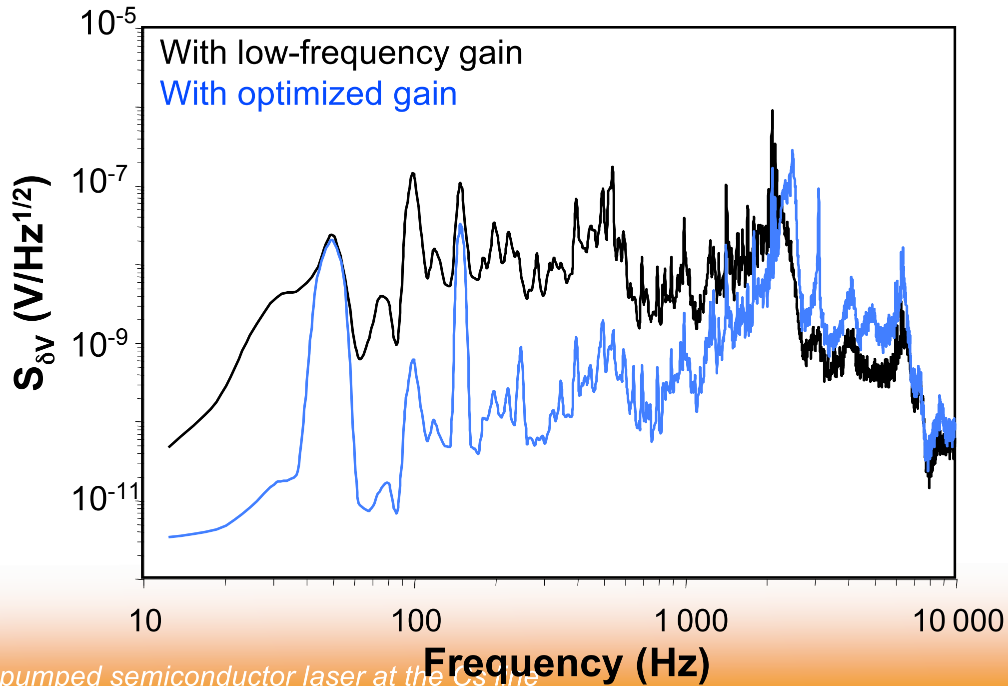
Beat-note set-up



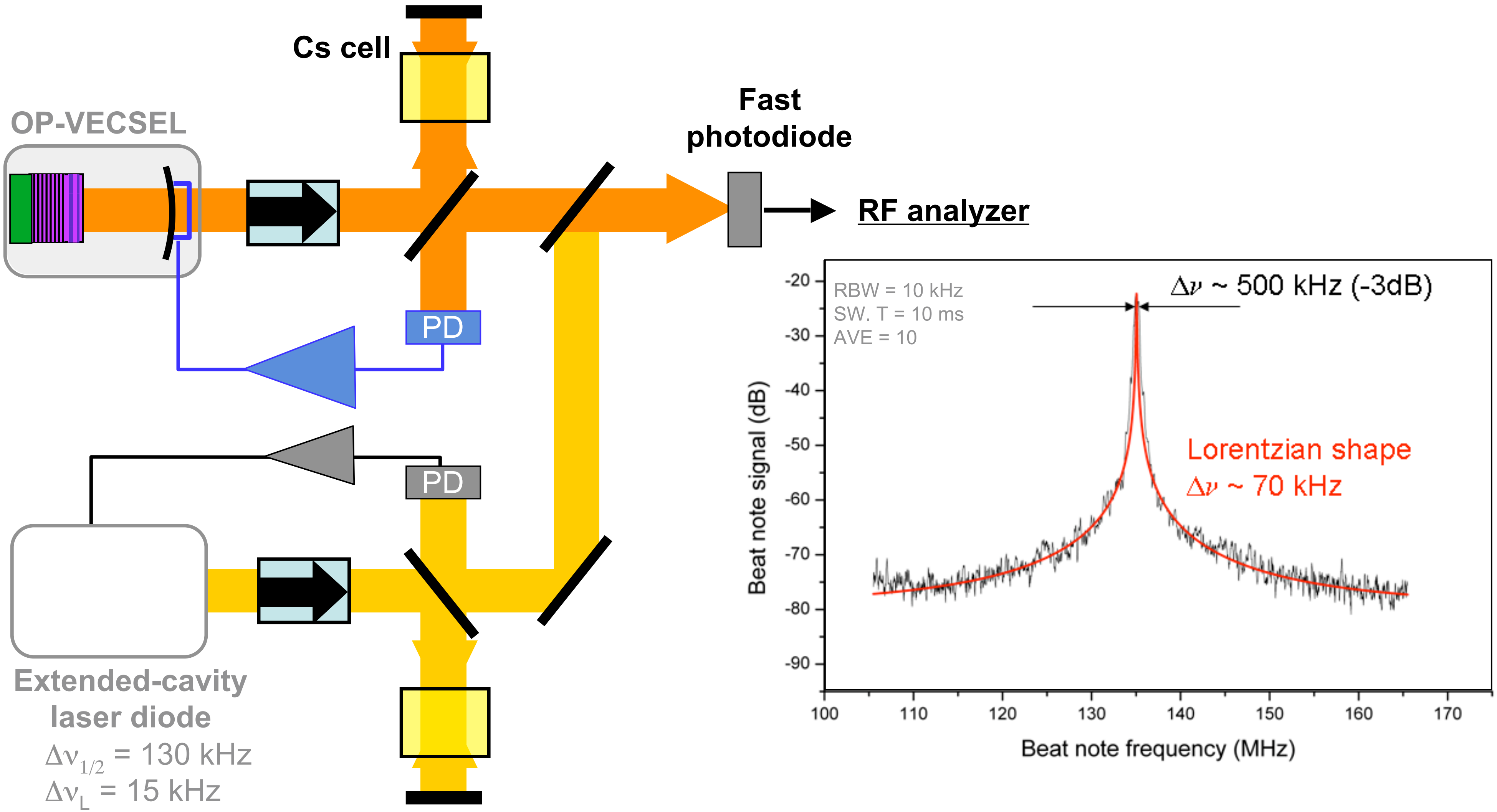
Baillard et al, Opt Comm (2006)

Stabilization of the laser frequency

- at side of a Doppler-free Cesium line (5 MHz FWHM)
- on PZT voltage - 2-stage integration electronics
- low-frequency servo loop (F < 2 kHz)

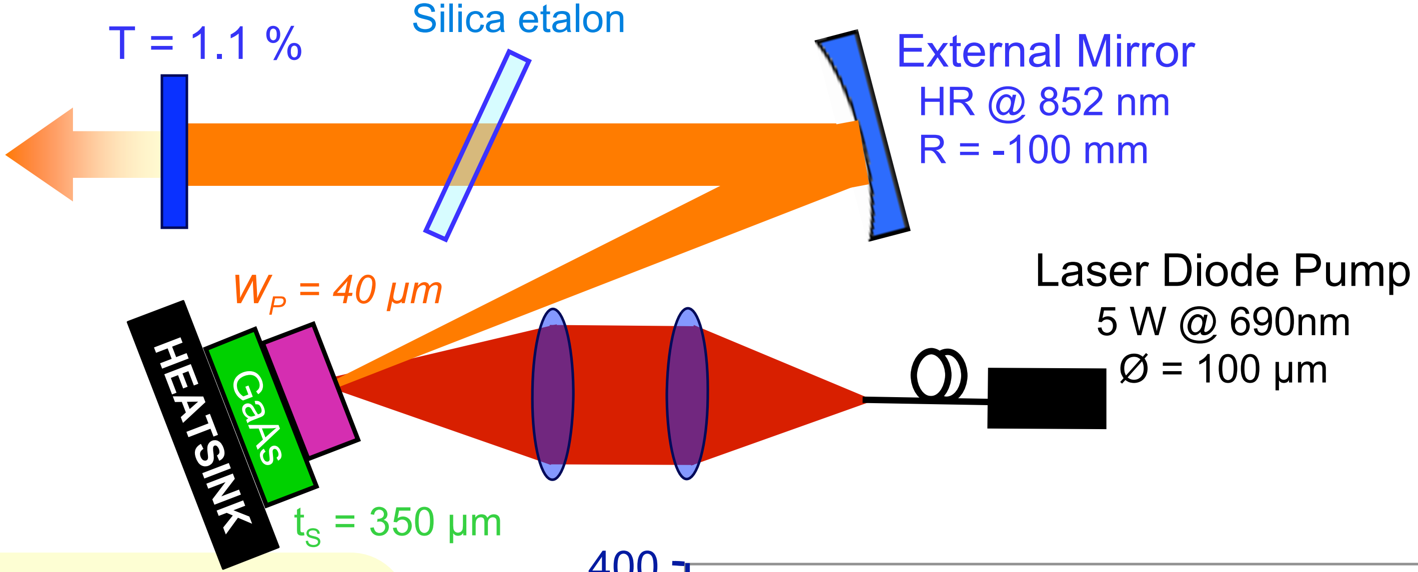


Linewidth measurement



- FWHM linewidth ≅ 500 kHz : low-frequency noise contribution
- Lorentzian linewidth ≅ 70 kHz related to white noise floor

Towards higher power…

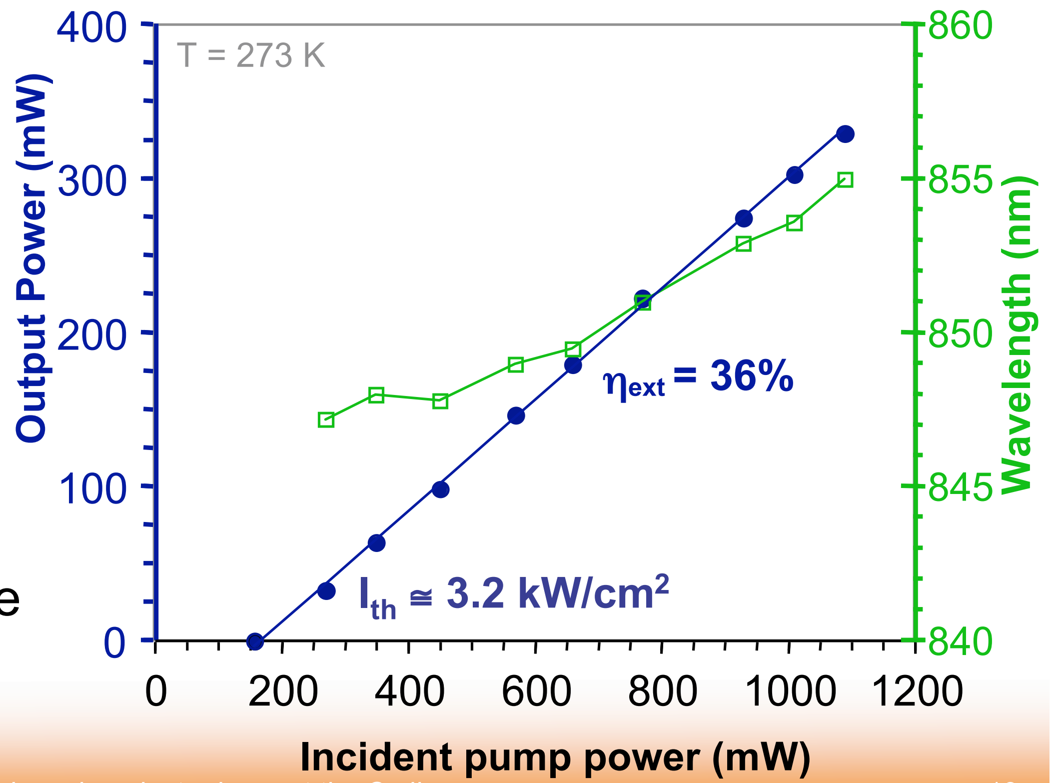


- **330 mW at P_P = 1.1 W**
  λ = 855 nm (Δλ ≅ 1 nm)

  450 mW under QCW pumping

- **Single transverse mode**

- **120 mW single-frequency**



⇒ Thermal-limited output power

⇒ **High output power** on a GaAs substrate

⇒ Low threshold & high opt-opt efficiency

Conclusion

– Design & fabrication of a AlGaAs/GaAs structure at λ = 852 nm optimized for low power/high efficiency operation

7 QWs

low threshold $I_{th} \leq 4$ kW/cm^2

– Single-frequency operation in a simple linear cavity

without λ-selective element : 17 mW

with a 25-µm thick etalon : 7 mW

} at 852.14 nm

– Validation on a Cs atomic line

>15 GHz continuous tunability

frequency lock-in on an absolute reference (*atomic line*)

comparison with an independent laser source :

$\Delta\nu_L$ = 500 kHz (-3dB / 10 ms *sweep time*)

Specifications already adequate for optical detection in atomic clocks

– Increase of the single-frequency power under high power pumping

120 mW without specific thermal management

(GaAs substrate, no intracavity heatspreader)

⇒ evaluation of the spectral properties

+ thermal management for power scaling